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DETERMINATION OF NEUTRON SPECTRA IN A COUPLED GRAPHITE-D_2O REACTOR

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ABSTRACT. The author analyzes on the basis of two-group theory the effect on K_∞ of indeterminateness of the spectrum in the case of measurements made with the reactor RB1 under certain conditions. He concludes that when charged with 7 to 13 fuel elements and used under the specified conditions the reactor RB1 exhibits the characteristics of an infinite reactor and that determination of the spectrum is of no great importance, but that efforts should be made to produce or obtain suitable structural materials to delimit the zone under examination.

1. Introduction

With the development of nuclear engineering the necessity arises of /5* minimizing the cost of experiments in neutron physics connected with the optimization of a planned nuclear power reactor.

For that purpose critical experiments have been gradually eliminated in favor of exponential or substitution experiments, by which the quantity of fuel under examination is greatly reduced.

In any case, when it is desired to carry out optimization studies of a particular reactor or studies of a special fuel element (for example elements containing plutonium), even substitution experiments become extremely costly.

To carry out the experiments just mentioned, one fairly economical way is the "reactivity zero" method perfected a few years ago by technicians of the PCTR (Physical Constant Testing Reactor) at Hanford [1]. Obviously the more it deviates from the critical experiments the more serious the problem of determining the neutron spectrum becomes and the larger the corrections for this mismatching.

Measurements of K_∞ done by the method of reactivity zero are in fact often criticized and rendered doubtful because of this type of correction.

The purpose of this article is to analyze by two-group theory the effect upon K_∞ of the non-determination of the spectrum in the particular case of measurements carried out with the reactor RB1 [2,3] with the central part moderated with D_2O and containing from 7 to 13 fuel elements of the type ECO [4] and of the type Cirene [5]. This study was arranged within the framework

*Numbers in the margin indicate pagination in the foreign text.

of the collaboration between the CNEN-EURATOM-CISE association and the Laboratorio Misure Parametri Reticolari del Centro di Calcolo (Laboratory for Measurements of Lattice Parameters of the Computer Center) at Bologna.

2. Outline of the Reactivity Zero Method /6

The "reactivity zero" method for measurement of K_∞ was developed, as has been mentioned, by researchers of the PCTR [1]. This is not the place to describe the method in detail, but, as we shall see later, it is necessary to discuss it briefly.

This method is essentially based on the fact that the reactivity of an infinite critical reactor does not change if a vacuum is maintained at the post of one side of it. This statement is valid even for a finite reactor provided the conditions typical of an infinite reactor are reproduced in it, namely:

a) Constant spatial distribution of the neutron density;

b) Neutron energy distribution not dependent on the position, in homogeneous media or media which have a periodicity equal to that of the cell for homogeneous media.

While it is fairly easy to obtain a constant distribution of the neutron flux, spectral determination is more complex.

To evaluate the importance of the error in K_∞ due to non-determination of the spectrum, D.D. Lanning [1,6] has derived the following formula on the basis of a two-group theory of perturbation:

$$\delta(K_\infty) = - \frac{(\phi_1'/\phi_2' - \phi_1/\phi_2)\,(\phi_1^{+\prime}/\phi_2^{+\prime} - \phi_1^{+}/\phi_2^{+})}{(\phi_1/\phi_2)\,(\phi_1^{+}/\phi_2^{+})} \qquad (1)$$

The quantities ϕ_1/ϕ_2 and ϕ_1^+/ϕ_2^+ are the ratios of fast fluxes to thermal fluxes, normal and adjoint respectively; the values with the prime refer to the zone under examination, while the values without the prime refer to the infinite critical mass. If the medium taken into consideration does not have $K_\infty = 1$, then what has been said refers to an infinite reactor poisoned by a thermal absorbent until $K_\infty = 1$ is obtained.

In the present study the quantities ϕ_1/ϕ_2 and ϕ_1^+/ϕ_2^+ do not always refer to unpoisoned media even if the K_∞'s of such media are greater than 1. Such approximations do not introduce significant variations into the results obtained, which, moreover, have largely a qualitative value.

3. Method of Calculation

The calculation was undertaken in the following manner:

a) The study concerned the reactor RB1 loaded with 9, 13, or 7 fuel elements under examination in the zone containing D_2O;

b) The geometry r,z of the reactor was changed to the geometry x,y

according to suitable schematizations;

c) The ϕ's and ϕ^+'s were calculated for the reactor with the zone loaded with fuel elements varying in number and cross section and the ϕ's and ϕ^+'s calculated for the equivalent infinite lattices; /7

d) The error $\delta(K_\infty)$ was calculated by formula (1).

In order to make a test of the goodness of the method of calculation, as a first step a theoretical evaluation was done of the mismatching of the flux in the central zone of the reactor RB1 loaded with elements of the ECO type.

By this procedure it was possible to compare some experimental results with the values obtained by calculation; the agreement between the theoretical values and the experimental data permitted us to attribute a significant degree of credibility to the calculations carried out on lattices of the Cirene type [7], for which no experimental data are yet available.

3a. Description of the Loading of the Reactor with ECO Elements

The reactor RB1 transformed to carry out experiments with lattices moderated with D_2O is described in detail in reference [5], but let us briefly review its most significant characteristics. In the central well of the reactor, diameter 100 cm, is arranged an aluminum container in which may be inserted up to 13 fuel elements of the ECO type; the multiplying zone is of graphite and contains up to 46 fuel elements (tablets of UO_2 enriched 20%). In the multiplying zone and the aluminum container are arranged 50 plates of the MTR type originating in the reactor ROSPO [8]; it was necessary to add these plates to compensate for the significant absorption due to the introduction of the container (ΔK_{eff} = -6%).

Usually the measurements are done with 9 elements of the ECO type, one central and 8 peripheral. The latter may be moved farther from or closer to the axis of the reactor by an adjustment effected from the outside so that the desired configuration is achieved.

Because of mechanical limitations it is only for the smaller size (18.8 cm) that it is possible to have a regular lattice composed of 13 fuel elements (see Figure 1).

3b. Schematizations of the Geometry of the Reactor

To be able to carry out calculations of the distribution of fluxes taking into consideration the heterogeneous loading of the central part of the reactor (the part of interest for measurement), certain approximations turned out to be necessary. The first of these approximations consists in considering only the pattern of the fluxes in the median plane of the reactor; the second approximation consists in schematizing the actual circular geometry of Figure 1 into a geometry of the type x,y (see Figure 2); and lastly, for the central zone a heterogeneous scheme was adopted (ECO-type fuel element distinguishable by the D_2O) and for the multiplying zone made of graphite, a homogeneous scheme using the mean macroscopic collision sections of the equivalent cell (Wigner's theory) was adopted.

3c. Determination of the Fluxes and of the Adjoint Fluxes

The calculation of the ϕ's and of the ϕ^+'s was effected by the configuration shown in Figure 2, with the nuclear code PDQ, adopting the two-group scheme of neutrons. Since this nuclear code, used because of the remarkable capacity of mesh points, does not compute the ϕ^+'s, for the calculation of these last the matrix was inverted and the code re-run after the performance of suitable substitutions in the collision sections. /8

The usual equations of two-group diffusion for a critical reactor, expressed in the form of a matrix, are:

$$\begin{vmatrix} [D_1 V_r^2 - \Sigma_{a1} - D_1 B_z^2 - \Sigma_R + \frac{\nu\Sigma_{f1}}{\lambda}] & \frac{\nu\Sigma_{f2}}{\lambda} \\ \Sigma_R & [D_2 V_r^2 D\, B_z^2 - \Sigma_{a2}] \end{vmatrix} \begin{vmatrix} \phi_1 \\ \phi_2 \end{vmatrix} = 0 \qquad (2)$$

and the adjoint equations are:

$$\begin{vmatrix} [D_1 V_r^2 - \Sigma_{a1} - D_2 B_z^2 - \Sigma_R + \frac{\nu\Sigma_{f1}}{\lambda}] & \Sigma_R \\ \frac{\nu\Sigma_{f2}}{\lambda} & D_2 V_r^2 - D_2 B_z^2 - \Sigma_{a2} \end{vmatrix} \begin{vmatrix} \phi_1^+ \\ \phi_2^+ \end{vmatrix} = 0 \qquad (3)$$

The adjoint matrix is obtained from the normal matrix by the following substitutions:

$$\begin{aligned} [\ \Sigma_R\ ]^+ &\longrightarrow \frac{\nu\Sigma_{f2}}{\lambda} \\ [\ \Sigma_{a1}]^+ &\longrightarrow \Sigma_{a1} + \Sigma_R - \frac{\nu\Sigma_{f2}}{\lambda} \\ [\ \nu\Sigma_{f1}]^+ &\longrightarrow \frac{\nu\Sigma_{f1}}{\lambda} \end{aligned} \qquad (4)$$

where the symbols are the standard ones and λ is the eigen value of the system.

Solving equations (2) and (3) with $\lambda \neq 1$ does not represent studying /9 the correct pattern of ϕ and ϕ^+ relative to an experimental situation, for in the latter we always have $\lambda = 1$.

To obtain the correct distribution of ϕ and ϕ^+ for a definite experimental situation we must proceed in the following manner:

1) Calculate the Σ_a, $\nu\Sigma_f$, etc., of the multiplying zone as functions of

the number of fuel elements situated in that zone;

2) Do a calculation of the K_{eff} of the reactor, adjusting the central D_2O zone as the experimental situation requires and seeking for the multiplying zone a situation relative to a certain number of fuel elements.

3) If the K_{eff} obtained by the calculation described in point 2) is not equal to 1, seek for the multiplying zone a situation relative to a different number of fuel elements and calculate the new K_{eff} of the reactor;

4) Repeat on the composition (i.e. the number of fuel elements) of the multiplying zone until K_{eff} is obtained equal to 1;

5) At this point invert the matrix and calculate the adjoint fluxes.

This proceeding is rather long and costly in view of the considerable amount of computer time involved.

For that reason, in the present study it was considered proper to adopt the above procedure only for one case, while for all other cases only one iteration was done. This, as has already been remarked, involves an error in the calculation of ϕ and ϕ^+, and consequently in the calculation of δK_∞. However, since the main purpose of this study is to have an evaluation in terms of order of magnitude of the effect of this spectral "mismatching," it may be said that such a calculation of ϕ and ϕ^+ is sufficiently accurate.

3d. Evaluation of the Error δK_∞ for the Various Lattices

The table shows the values of

$$\frac{\Delta(\phi_2/\phi_1)}{(\phi_2/\phi_1)}, \frac{\Delta(\phi_2^+/\phi_1^+)}{(\phi_2^+/\phi_1^+)} \text{ and of } \delta(K_\infty)$$

in the various cases studied. The quantities

$$\frac{\Delta(\phi_2/\phi_1)}{(\phi_2/\phi_1)} \text{ and } \frac{\Delta(\phi_2^+/\phi_1^+)}{(\phi_2^+/\phi_1^+)}$$

are understood as means of the variations of ϕ and ϕ^+ around the central element.

The first case in the table has reference to a loading with 13 ECO fuel elements (cf. Figure 2). The D_2O is poisoned with copper until the K_∞ of /10 the corresponding infinite lattice is obtained equal to 1; moreover, in the central zone $B_z^2 = 0$, while in the peripheral zones $B_z^2 = 1.34 \cdot 10^{-4}$ cm^{-2}, corresponding to the transverse buckling obtained by a best fit of experimental flux values. For this case the complete procedure outlined in Section 3c was followed.

Case II has reference to a loading with 13 ECO elements as before, but with the D_2O not poisoned.

Table

Case No.	Loading of RBI Central Zone	$\frac{\Delta(\phi_2/\phi_1)}{(\phi_2/\phi_1)}$ in %	$\frac{\Delta(\phi_2^+/\phi_1^+)}{(\phi_2^+/\phi_1^+)}$ in %	$\lvert\delta(K_\infty)\rvert$ in ‰
I	13 ECO elements ($K_\infty = 1$)	1.0	0.4	< 0.1
II	13 ECO elements	3.1	1.5	0.5
III	13 ECO elements (half density)	2.1	2.4	0.5
IV	9 ECO elements	1.4	1.5	0.2
V	7 ECO elements	1.0	1.7	0.2
VI	7 Cirene elem.	3.7	1.7	0.6

Since there were some doubts as to the calculation of the constants of the zone designated as "tank + ROSPO layer," in case III the densities of the elements of that zone were halved and the $\delta(K_\infty)$ evaluated with reference to the situation of the preceding case.

In case IV, loading with 9 ECO bars was studied, as obtained by the arrangement shown in Figure 2, without the 4 outside elements; in case V, loading with 7 ECO bars, analogous to the loading of Figure 3. In case VI the RB1 was loaded with 7 bars of the Cirene type (cf. Figure 3).

This last case is perhaps the most important for our purposes, inasmuch as the study reported in this article was carried out to see whether 6 fuel elements of the Cirene type are sufficient to determine the neutron spectrum so that the measurements of K_∞ will not be significantly affected by energy transients. /11

As may be seen from the data given in the table, when formula (1) is used values of $\delta(K_\infty)$ below 1‰ are obtained. These results show that the K_∞'s are not appreciably influenced by spectrum variations that occur outside the 8 or 6 peripheral cells. This result has been confirmed by experiment.

The experimental data, which will be given in an early joint EURATOM-CNEN report, show that the CdR of some types of resonance detectors in the central zone of the reactor does not vary significantly even when that value varies greatly outside the peripheral cells. Figure 4 shows diagrammatically the experimental situation in which the measurements were carried out. Figure 5 shows the computed variation of ϕ_2/ϕ_1, a quantity proportional to (CdR - 1) in the infinite case (curve I), in the case of 9 fuel elements (curve II), and in the case of 13 fuel elements (curve III). These curves were obtained along the line of dashes of Figure 4. As may be seen from Figure 5, in the zone of measurement the ratio ϕ_2/ϕ_1 is practically independent of the fluctuation that

this value has outside the peripheral cells. These cells are a kind of "wave-breaker" for the transients of the energy spectrum. This does not occur in the case of graphite moderated lattices, inasmuch as the area of migration of these lattices is far larger than that of D_2O moderated lattices ($M^2_{graphite}$ = 1000 cm^2 as compared to $M^2_{D_2O}$ = 350 cm^2) and therefore the zone under examination, in the unit M, comes out much smaller for the charge of the graphite type than for the D_2O charge.

Conclusions

/12

Although the calculation is only indicative in character because of the various approximations used (diffusion theory even inside the bar, use of the perturbative formula (1), transfer from the (r,z) geometry to the (x,y) geometry), the results are very gratifying -- $\delta(K_\infty)_{max} < 1‰$ even for a number of peripheral cells of the order of 6. It is therefore concluded that the RB1, for these lattices moderated with D_2O and containing from 7 to 13 of the elements in question, exhibits in its interior zone the characteristics of an infinite reactor consisting of the lattice in question, even in the case of fuel elements of large section, such as the "Cirene" elements.

The problem of determination of the spectrum, when measurements are done on D_2O moderated lattices, loses a great deal of its importance, and it seems therefore that the greater efforts should be expended on measuring correctly the final pattern of the flux in the fuel element, which in these types of lattice often has a very complicated geometry, and on preparing or selecting the necessary structural materials, for example, to delimit the zone under examination.

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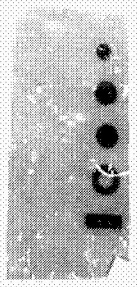

Openings for Standard Fuel Elements
Counters
Gravity Bar
ECO Fuel Elements
ROSPO Fuel Elements

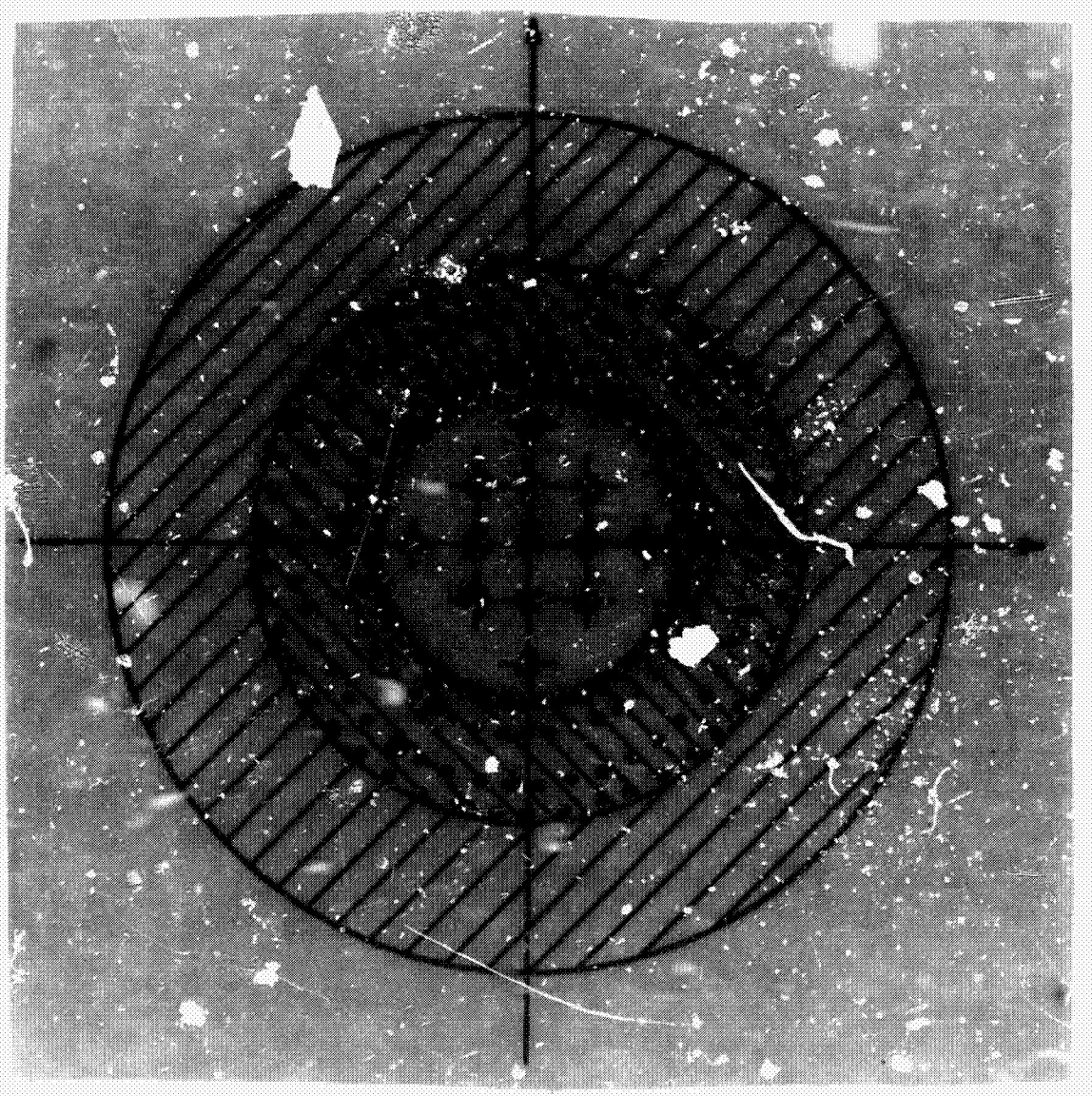

Figure 1. Horizontal Section of the Reactor RB1 with Central Zone Containing 13 ECO Elements

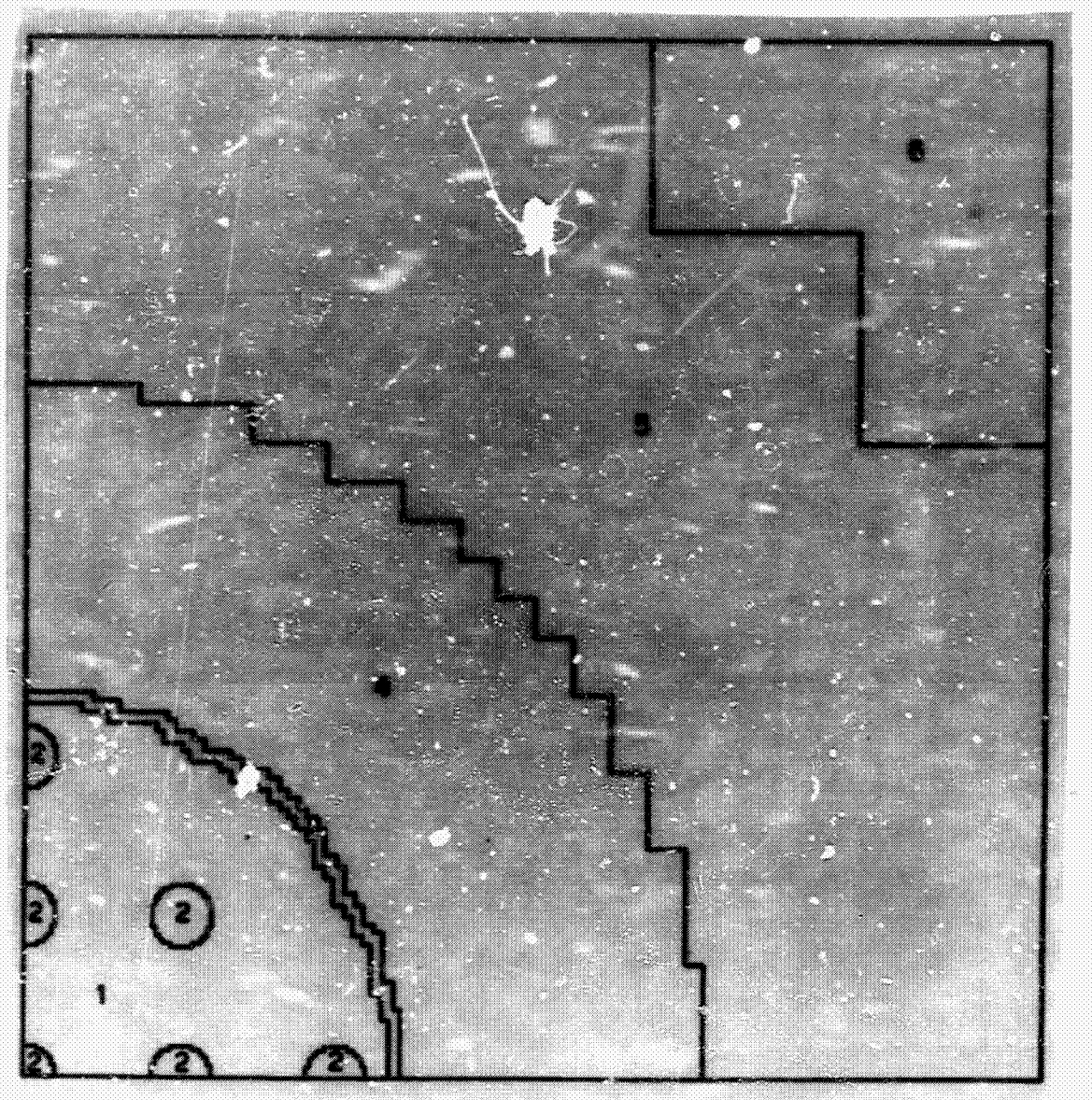

Figure 2. Diagram of RB1 with 9 to 13 ECO Fuel Elements

1 - Heavy Water

2 - ECO Fuel Element

3 - Aluminum Tank + ROSPO Plate

4 - Multiplying Zone, Graphite + RB1 Elements

5 - Reflector

6 - Absorbent

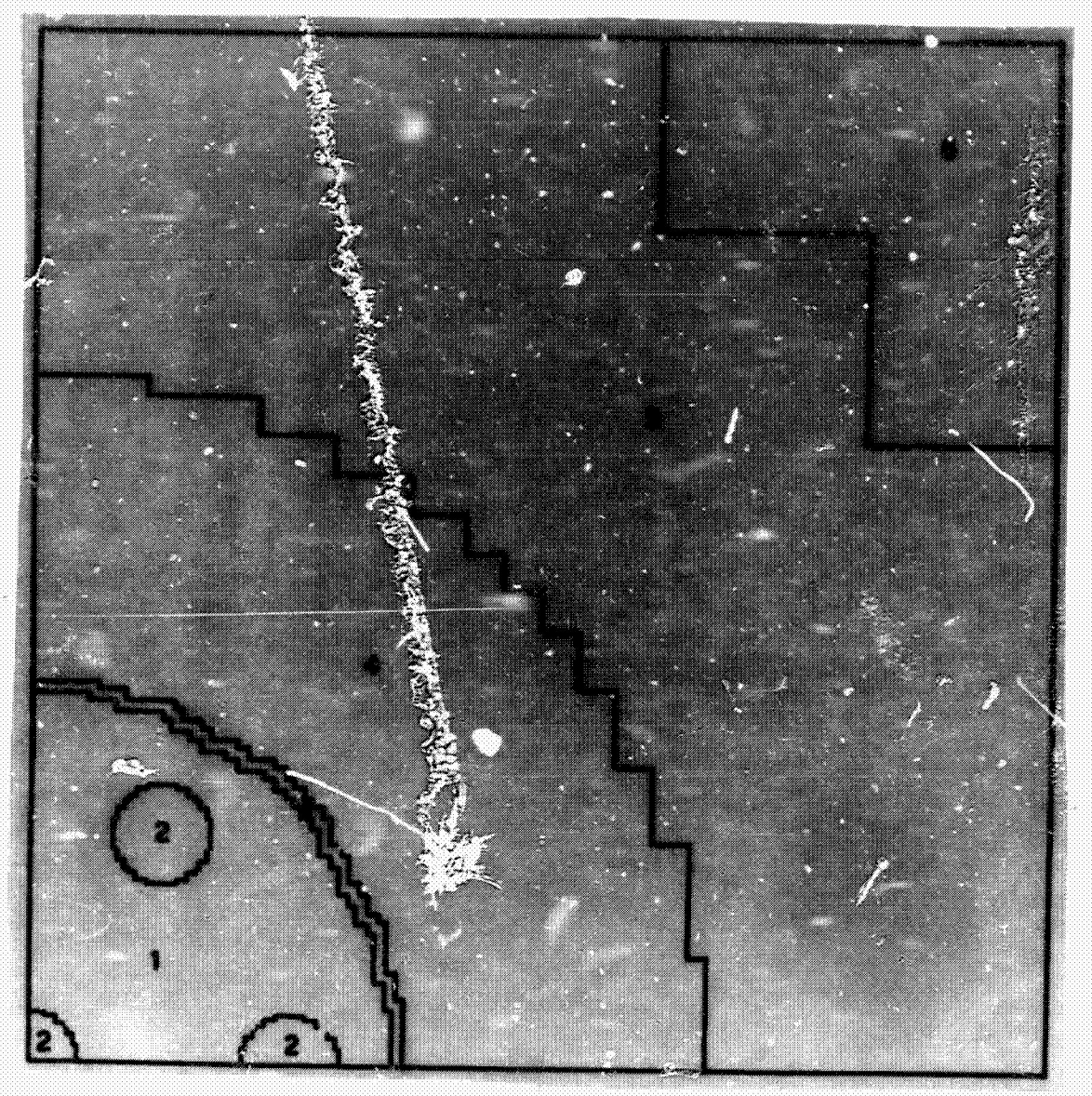

Figure 3. Diagram of RBl with 7 CIRENE Elements

1 - Heavy Water

2 - CIRENE Fuel Element

3 - Aluminum Tank + ROSPO Plate

4 - Multiplying Zone, Graphite + RBl Elements

5 - Reflector

6 - Absorbent

Figure 4. Diagram of the RB1 with 13 ECO Elements

1 - Heavy Water

2 - ECO Fuel Element

3 - Aluminum Tank + ROSPO Plate

4 - Multiplying Zone, Graphite + RBi Elements

5 - Reflector

6 - Absorbent

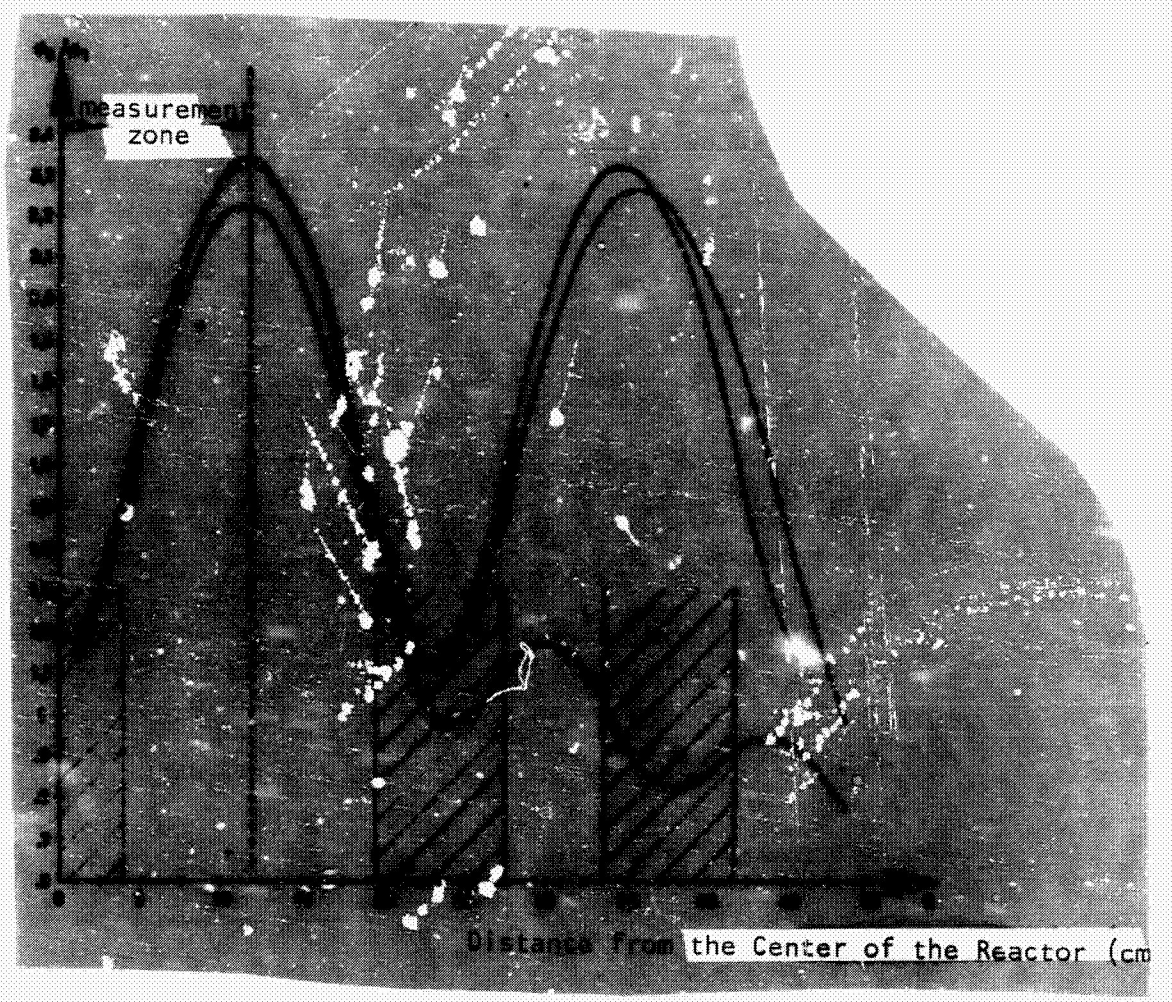

Figure 5. Curve of ϕ_2/ϕ_1 for the Configuration of Figure 4

------- Infinite reactor

-·-·-·- Charge corresponding to 9 ORGEL Elements

——— Charge corresponding to 13 ORGEL Elements

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